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Macroanalysis of the economic and environmental impacts of a 2005–2025 European Union bioenergy policy using the GTAP model and life cycle assessment

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ABSTRACT

This paper describes a new tool to assess the medium- and long-term economic and environmental impacts of large-scale policies. The approach – macro life cycle assessment (M-LCA) – is based on life cycle assessment methodology and includes additional elements to model economic externalities and the temporal evolution of background parameters. The general equilibrium model GTAP was therefore used to simulate the economic consequences of policies in a dynamic framework representing the temporal evolution of macroeconomic and technological parameters. Environmental impacts, expressed via four indicators (human health, ecosystems, global warming and natural resources), are computed according to policy life cycle and its indirect economic consequences. In order to illustrate the approach, two 2005–2025 European Union (EU) energy policies were compared using M-LCA. The first policy, the bioenergy policy, aims to significantly increase energy generation from biomass and reduce EU energy demand for coal. The second policy, the baseline policy, is a business as usual policy where year 2000 energy policies are extended to 2025. Results show that, compared to the baseline policy, the bioenergy policy generates fewer impacts on three of the four environmental indicators (human health, global warming and natural resources) at the world and EU scales, though the results may differ significantly at a regional level. The results also highlight the key contribution of economic growth to the total environmental impacts computed for the 2005–2025 period. A comparison of the results with a more conventional consequential LCA approach illustrates the benefits of M-LCA when modeling the indirect environmental impacts of large-scale policies. The sensitivity and uncertainty analysis indicates that the method is quite robust. However, its robustness must still be evaluated based on the sensitivity and uncertainty of additional parameters, including the evolution of economic growth.

Contents

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1. Introduction

With the continuous increase in human activities, natural resource depletion (e.g. oil depletion) and pollutant emissions have become major challenges to future development. An awareness of the impacts of human activities on ecosystems (e.g. eutrophication of lakes and rivers) and more recently on the climate (global warming) has led to the development and application of various environmental policies (e.g. Kyoto Protocol). In fact, many climate change mitigation policies are focused on replacing fossil fuels with renewable energy sources: 149 renewable energy policies were applied in the past around the world and 778 are currently in force [1]. Because fossil fuels are currently used extensively in energy generation, accounting for 81% of the world's primary energy in 2007 [2], the implementation of the energy transition will take decades. In the climate change mitigation context, energy policies are therefore often based on long-term objectives.

It has been shown that an environmental policy can lead to unexpected and unwanted environmental impacts. For instance, Searchinger et al. [3] demonstrated that large amounts of biomass used to produce biofuels and replace fossil fuels could lead to the release of a significant amount of greenhouse gas (GHG) emissions into the atmosphere as natural lands are converted to crop lands. Also, Greening et al. [4] and Hofstetter and Norris [5] documented various rebound effects with negative environmental impacts. These examples illustrate the need to assess environmental policies with tools that take the full range of environmental consequences into account. Of all the environmental evaluation methods, life cycle assessment (LCA) seems especially adapted, since it makes it possible to compute the potential environmental impacts generated by natural resource extraction and the release of pollutant emissions at each stage of the life cycle of a given product or service[1]. The methodological consensus on LCA is defined in the ISO standards (ISO 14040 and 14044) and often referred to in the literature as attributional LCA [6].

However, certain environmental impacts caused by product changes may occur outside the life cycle, and would thus be ignored in an attributional LCA [6–20]. For this reason, a new form of LCA, referred to as consequential LCA (C-LCA), was developed [21–26]. C-LCA focuses on the environmental consequences of a change occurring in a given life cycle, regardless of whether these consequences occur within or outside the life cycle. It should be noted that the C-LCA approach presented in the literature is designed to assess the environmental consequences of minor disturbances affecting one or a few life cycles and may not be well-suited to studying significant perturbations affecting several life cycles, such as in the case of the implementation of an energy policy. Moreover, in C-LCA, it is often assumed that the world remains unchanged during the perturbation period. This assumption may be valid for small changes occurring in the short term but could come into question for significant disturbances occurring over a long period of time. In this case, ignoring the evolution of the economy could significantly impact the results, since it is likely that the consequences of a disturbance are affected by economic [27,28] and technological [26,29] evolution.

Solutions have been advanced to take the technological innovations in LCA into account, notably by introducing the concept of prospective LCA (P-LCA) [30–35]. In P-LCA, data are supposed to be representative of future technologies but, because the future is uncertain, authors often use prospective scenarios to manage uncertainty [33,36–39]. However, because P-LCA focuses on a given life cycle affected by technological evolution, it does not model the evolution of the entire economy. Therefore, while it could be useful to merge P-LCA and C-LCA to study significant changes occurring in life cycles over a long period of time, the method would not be sufficient because the evolution of the economy would be still ignored. This paper therefore proposes a new LCA approach, macro LCA (M-LCA), which includes elements of P-LCA and economic modeling that are suitable for the evaluation of the environmental consequences of large-scale disturbances affecting life cycles and occurring over a long period of time. This new approach is an extension of the work presented in Dandres et al. [28] that models the evolution of the economy and includes technological innovation. The M-LCA approach is illustrated using a case study of the environmental impacts of two energy policies. Finally, the results obtained using the M-LCA approach are compared with those obtained using the C-LCA approach.

2. Methods

The objective of the case study is to assess the global environmental impacts brought about by heat and electricity generation in the European Union (EU) between 2005 and 2025 based on two prospective EU energy development scenarios detailed in the following section. The EU energy sector was modeled based on its life cycle following the P-LCA approach, as described in the next section. Though EU energy generation is the main focus of the case study, the scope was extended to the entire world and all economic sectors in order to include the indirect environmental consequences of each EU energy scenario that may occur in other regions and economic sectors. The macroeconomic GTAP was therefore used, as described in Section 2.3. Also, in light of the long temporal horizon, technological and economic evolutions are taken into account, as described in Section 2.4. Fig. 1 summarizes the M-LCA approach within the context of the aforementioned case study. Finally, the case study was also carried out based on a C-LCA approach in order to compare the C-LCA and M-LCA approaches. The application of the C-LCA approach to the case study is described in Section 2.5.

2.1. European energy scenarios

Mantzos et al. [40] designed several scenarios to describe possible developments in the EU energy sectors (electricity, heat, steam and transport) up to 2030. These scenarios were generated using the PRIMES model for the European Commission [41]. PRIMES is a partial equilibrium economic model designed to predict the evolution of European energy markets based on the changes in

[1] To be brief, later in the text, the term *product* will mean both product and service.

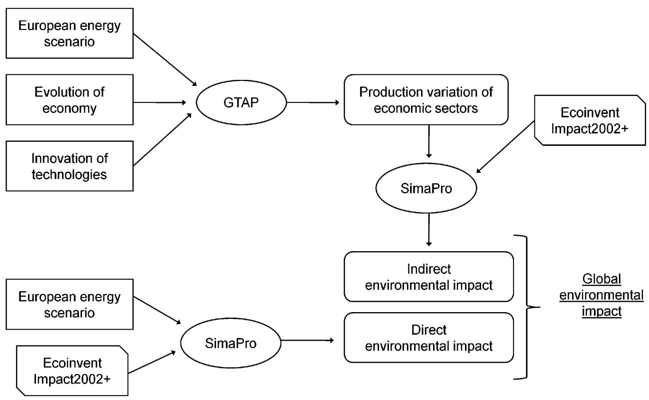

Fig. 1. Overview of the macro life cycle assessment (M-LCA) method.

prices, demand and supply of each energy source in each European country. The main objective of the model is to study the economic impacts of various European energy policies on the energy sectors. For the purposes of this study, Mantzos *high levels of renewables* scenario (referred to in this paper as the *bioenergy* scenario) was chosen because it involves significant changes in the European energy sector over several decades. More specifically, large amounts of biomass are used in the electricity sector to replace coal (see Fig. 2).

A second scenario, the Mantzos *baseline* scenario, which corresponds to the business as usual development of the European energy sector, was also studied to express the environmental impacts of the bioenergy scenario relative to the business as usual situation. Thus, it is possible to determine whether the environmental impacts of the bioenergy scenario are more or less significant than those of the baseline scenario. Moreover, comparing the scenarios makes it possible to distinguish the environmental impacts generated by a bioenergy policy from those generated by economic growth (which is similar in both scenarios). The study period was set at two decades, 2005–2025, in order to observe the effects of global technological and economic evolutions.

2.2. European energy sector

Direct environmental impacts, defined as the extraction of natural resources and the emission of pollutants by the European energy sector in 2005–2025, were studied using P-LCA to include technological evolution during the period. Concretely, the EU energy sector was modeled according to an A-LCA methodology using the ecoinvent database version 2 [42]. However, the efficiency of each technology presented in Mantzos et al. [40] was increased based on a yearly average growth rate found in literature [43–46]. Then, the direct environmental impacts of the European energy sector were computed based on EU electricity and heat demands in 2005–2025 using the SimaPro LCA software version 7 [47] and IMPACT2002+ version 2.05 [48] impact assessment method. The authors chose not to assess the environmental impacts of the EU biofuel policy designed in Mantzos et al. [40] because biofuel policy modeling would have called for major changes to the GTAP model and GTAP7 database: the introduction of agro-ecological zones [49] and land supply curves [50] to overcome the land use modeling limitations of the GATP model and a disaggregation of the GTAP7 database to model oil biofuel and sugar crop biofuel separately. However, this is not a significant issue in this paper, since the goal is to propose and illustrate a new method rather than compute precise results. Additionally, the environmental impacts of the EU transport sector are not ignored but modeled in the indirect environmental impacts, as described in Dandres et al. [28].

2.3. Consequential approach at the macro level

The Mantzos scenarios were expected to affect several economic sectors and, as a result, the environment as well. It was therefore decided to model the consequences of this type of policy using a general equilibrium macroeconomic model, as recommended in economic studies [39,51,52]. The consequences of both Mantzos scenarios on the global economy were modeled using the GTAP economic model, a general equilibrium model that simulates the world economy through 57 economic sectors and 113 regions according to changes in economic parameters [53]. Regions and economic sectors were aggregated into 14 regions and 20 sectors, as detailed in Tables 1 and 2 so as to reduce computing resource requirement. Simulations were conducted separately for each energy scenario based on the variations in fuels demand for electricity and heat as inputs in the GTAP model. The economic and technological changes described in the next section were also included as input in the GTAP simulations. Production variations for each economic sector in each region of the world were used according to the LCA method to calculate the indirect environmental impacts of each scenario. The life cycle of each economic sector was modeled using the technological processes found in the ecoinvent database. Finally, like the direct environmental impacts of the EU energy sector, the environmental impacts were computed using SimaPro

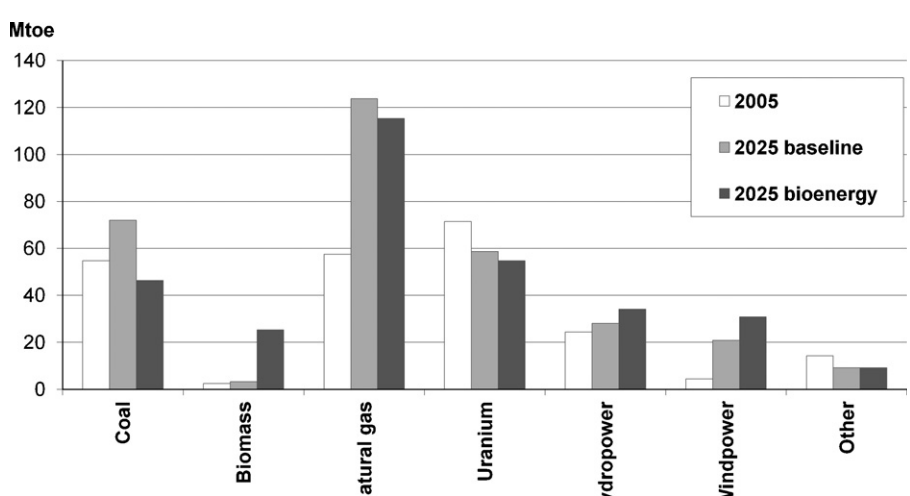

Fig. 2. Sources of electricity in the European Union in 2005 and 2025.

Table 1
Biomass supply in the conventional consequential approach.

Natural resource	Product type	Function (before 2005)	Consequences	
			Low constraints case	High constraints case
Residues from forestry and sawn wood industries	Dependent co-product[a]	Maintain soil quality	Collecting wood residues in forests leads to soil quality losses.	Wood residues are not collected in forests, and the soil quality remains the same.
Wood used by other industries	Determining product[b]	Produce paper pulp (only the paper industry is expected to be affected)	Not collected, and the paper industry is not affected.	Collecting wood affects paper industries. European pulp and paper productions must be compensated.
Residues from agriculture	Dependent co-product	Maintain soil quality	Collecting agricultural residues leads to soil quality losses that are compensated through the use of mineral fertilizers.	Collecting agricultural residues causes soil quality losses.
Residues from the food industry	Dependent co-product	Feed livestock	Not collected, and livestock is therefore not affected.	Collecting residues from the agri-food industry reduces the amount of food available for livestock. The lack of food for livestock must therefore be compensated
Crops	Determining product	Feed humans and livestock	The Schmidt methodology [44] is used to model affected systems.	

[a] A co-product is said to be dependent when demand for the co-product has no influence on its production.
[b] A determining product is defined as a product for which demand is directly linked to its production.

Table 2
Technical requirements.

	Comment
Minimum requirement	
GTAP-LCA model[a]	- A modified version of the GTAP standard model;
GTAP7 database	- Older versions will work but with lesser geographic/sectoral resolution;
ecoinvent-GTAP database[a]	- A modified version of the ecoinvent 2 database;
SimaPro	
	- Any LCA software compatible with ecoinvent will work.
Optional but recommended	
MDB 2004[a]	- Database built with data collected from UNDATA, FAOSTAT and IEA;
Microsoft Excel 2007	- Other spreadsheet software may require some modifications in the M-LCA template in order to work properly.
M-LCA template of the method[a]	- Step-by-step description of how to compute the environmental impacts (Microsoft Excel file);
GEMPACK	- To adapt the GTAP-LCA model to a specific M-LCA study;
Crystal Ball	- To conduct uncertainty analysis.

[a] These resources will be provided in the near future on the website of the CIRAIG at www.ciraig.org.

and IMPACT2002+. Methodological details (excluding technological innovation modeling) can be found in Dandres et al. [28].

In C-LCA, it is recommended to identify the technologies affected by the studied marginal change for specific modeling, since the environmental impacts may vary significantly between technologies producing a same product [21]. However, because the results of GTAP simulations showed significant production changes in almost all regional economic sectors, it was assumed that all technologies in all regional sectors were affected. Therefore, the affected technologies were not identified and average data were used to model each technology instead of specific data.

2.4. Prospective approach

Two temporal aspects were taken into account in the analysis: economic growth and technological innovation. These aspects are discussed in the following sections.

2.4.1. Economic growth

Expected economic changes in 2005–2025 were implemented in the economic simulations, as recommended by Toth [54] and Berck and Hoffmann [51]. Economic growth was modeled in GTAP simulations by varying the regional macroeconomic variables (population, capital, gross domestic product (GDP), and skilled and unskilled labor forces) according to future projections. Forecasted data were obtained from the United States Department of Agriculture [55] for population and GDP, from Poncet [56] for capital and from the International Labor Organization [57] for skilled and unskilled labor forces.

2.4.2. Technological innovation

Technological innovation was taken into account for each region and each economic sector as GTAP simulation input, and the model computed how the demand and production of each economic sector would be affected by technological changes. More specifically, GTAP modeled the commodities reduction required to produce a given commodity. In order to avoid counting commodity consumption reductions twice, the efficiency of the ecoinvent processes was not increased to reflect future technological advances because it would have resulted in another reduction of the commodities used to produce a given commodity. This constitutes one of the limitations of the study, since technological innovation leading to emissions reductions cannot be modeled this way. Ideally, specific data for each region and technology should have been collected from expert panels to model future regional and sectoral technological developments [36,58–62]. Should these situations occur, the emissions reductions would have been applied in the ecoinvent processes. However, considering the high number of regions and economic sectors (113 regions × 57 sectors) and the fact that each economic sector includes hundreds of technologies, average data for each economic sector rather than for each technology was collected to lessen the amount of time needed for data collection. Despite this simplification, data were difficult to find because technological changes are not widely documented, especially with regards to future technological changes. An indirect measurement

of technological change is the total factor productivity (TFP), which is commonly used by economists to monitor productivity changes [63–66]. However, TFP also includes other parameters that influence productivity: capital, labor, intermediate goods, land use and other externalities [67–69]. Therefore, TFP growth is generally not fully representative of technological innovation. Nevertheless, when TFP is computed using the Malmquist method [70], the contribution of technological change to TFP is explicitly known. Thus, in this study, technological changes computed based on the Malmquist method were used whenever possible. In other cases, TFP was used as a proxy to model technological innovation. Finally, in the cases in which no TFP data were available, the averages of the data available for the corresponding economic sector were used as a proxy. Projections of future TFP up to 2025 were used whenever available but, in most cases, TFP growth rate averages were computed from historic values (ideally from 1985 to 2005), assuming that past technological development trends will continue in the future up to 2025. This constitutes the second limitation to technological innovation modeling in this study, since the approach does not take the maturity of a technology into account (the more mature the technology, the less it is expected to improve). Also, TFP data for an economic sector in a specific region were used for every technology in the sector and region. This constitutes the third limitation to technological innovation modeling in this study, since technologies in a given economic sector may evolve differently.

2.4.3. Recursive simulations

Bergman et al. [52] recommend dynamic models to study long-term environmental policies to assess the internal fluctuations that may occur during a long period of time and this approach is indeed followed by many authors [50,71–85]. Therefore, the 2005–2025 period was divided into four sub-periods of five years to model the internal changes and environmental impacts taking place during each. The first GTAP simulation was conducted by implementing the technological, economic and EU energy sector changes for the 2005–2010 period. Then, the results of the 2005–2010 simulation were used to update the GTAP database. The 2010–2015 simulation was conducted with the updated GTAP database and based on the technological, economic and EU energy sector changes in the 2010–2015 period. This procedure was also followed to run 2015–2020 and 2020–2025 simulations.

2.5. Comparison with another consequential-prospective approach

The results obtained using the approach described above were compared with those obtained using a more conventional consequential LCA approach [21–26] in which technological innovation is modeled exactly in the same way as described above. The difference between the more conventional approach and the M-LCA approach lies in consequence modeling. While the M-LCA approach proposed in this paper models the economic and environmental consequences of the studied EU policies based on the GTAP model, the conventional C-LCA approach uses broad assumptions regarding biomass availability to define two extreme cases (Table 1).

In the first case, there are little constraints on biomass supply and most of the biomass required can be obtained from local forest, wood and agro-food industries without affecting the rest of the EU economy. Agricultural and livestock production remain unchanged. It is assumed that there is no competition for the additional residues required to generate energy since they would otherwise be left on the ground.

In the second case, constraints on biomass supply are more important, and some biomass must be imported from foreign countries or deviated from other industries to compensate. The following assumptions were made in the high constraints case:

- Due to availability constraints for certain residues, wood biomass must be imported from Eastern Europe [86].
- Pulp production in Europe has fallen because the wood is now consumed by the energy sector. It is assumed that the decrease in European pulp production is compensated through imports from Canada, the world's largest pulp exporter [87].
- Biomass residues usually left on the ground for soil fertilization are collected to generate energy. It is assumed that mineral fertilizers are used to maintain soil fertility. Fertilizers are identified by type based on the process presented by Weidema [23].
- Residues from the food industry are used to produce energy. This leads to a lack of nutriments for EU livestock. According to Weidema [23], missing nutriments are assumed to be compensated with barley produced in Canada using the method presented by Schmidt [16].

2.6. Sensitivity and uncertainty analysis

In order to assess the robustness of the M-LCA approach, a sensitivity and uncertainty analysis was conducted to compare EU energy policies. The analysis is based on the variation of a sensitive parameter of the GTAP model and the use of a statistical method applied to calculate the environmental impacts.

Among the parameters of the GTAP model, the elasticities of Armington, which handle the competition between domestic and foreign products, are often mentioned as an uncertain and very sensitive parameters that can significantly affect the results of the model [88–91]. Thus, several values for the Armington elasticities were used to test the sensitivity of the M-LCA approach to this parameter. One set of Armington elasticities was obtained by increasing the original values by 50% and another was obtained by decreasing them by 50%.

Monte-Carlo (MC) [92] statistical analysis are commonly conducted to manage uncertainty in LCA [93–98] and was used to manage the uncertainty generated by the data and models in LCA methodology. Monte-Carlo analysis aims to compute the results of a model a high number of times by varying all the parameters according to the values they could take inside a probability distribution specified for each parameter. The MC simulations were conducted in two sequences in order to reduce computing time:

1. MC simulations were run for each ecoinvent process used to model each GTAP economic sector in order to obtain probability distributions for each of the four environmental impact categories. These simulations were conducted with SimaPro software according to the uncertainty data available in ecoinvent database and IMPACT2002+ method.
2. The probability distributions of each ecoinvent process obtained earlier were used to compute the probability distribution of the environmental impacts of each EU energy scenario, and the MC simulations were computed with Microsoft Excel using the Crystal Ball plug-in [99].

In both cases, 1000 iterations were set out. Test MC simulations were conducted with 10 000 iterations, which took much more time and did not yield any significant differences in the results. In the second sequence of MC simulations, the standard deviation of each probability distribution was increased to take the uncertainty of the ecoinvent processes used as proxy into account. Indeed, there is always an uncertainty between the LCA database processes and reality, which can be defined according to several indicators gathered in a pedigree matrix, including temporal and geographical correlations [100]. In this study, ecoinvent processes (which are

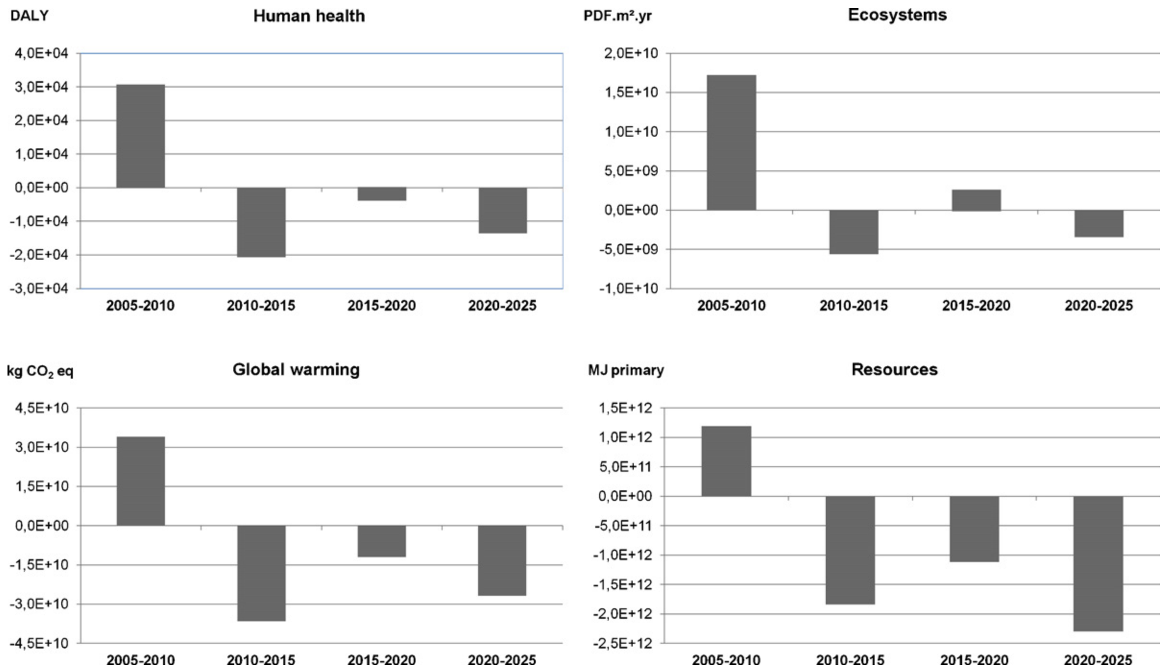

Fig. 3. Comparison of estimated potential environmental impacts of both scenarios by period based on IMPACT2002+.

almost entirely based on European data for year 2000) were used to model processes in all world regions and up to 2025. To assess the uncertainty resulting from the use of proxy processes, the pedigree matrix of some ecoinvent processes was edited in SimaPro. Results show that the standard deviation of the distribution of an ecoinvent process was multiplied by 2.5 when the best situation (regarding uncertainty) was compared to the worst. Therefore, in the second sequence of MC simulations, all standard deviations were multiplied by 2.5. This process probably exaggerates the uncertainty, but it would be too time consuming to manually specify the standard deviation of each process (Table 2).

3. Results and discussion

The first section presents the results of the comparison of the two energy scenarios. This comparison is made by time period at the world scale and then at the regional scale and by economic sector to provide a more extensive interpretation of the differences between the two scenarios. In the second section, the environmental impacts are expressed relative to 2005 to evaluate the performance of both policies in the context of technological evolution and economic growth in 2005–2025. The third section is a comparison of the results obtained with M-LCA and conventional C-LCA, followed by a discussion on their methodological differences and scopes of application. The fourth section details the sensitivity and uncertainty analysis of the results.

3.1. Comparison of European energy policies

3.1.1. By time period

A comparison of the direct and indirect environmental impacts of the baseline and bioenergy scenarios is presented as a function of the time period in Fig. 3. In this figure, the environmental impacts of the baseline scenario were subtracted from those of the bioenergy scenario to allow for a direct scenario comparison. This approach has the advantage of eliminating the impacts of the economic growth and focusing on the differences between the two scenarios. The results presented in Fig. 3 should therefore be interpreted as follows: a positive number indicates that the environmental performance of the bioenergy scenario is worse than the environmental performance of the baseline scenario, and a negative number indicates the better performance of the bioenergy scenario.

Simulation results show that, for the entire period at the global scale, the impacts of the bioenergy scenario relative to the baseline scenario are less significant for human health, GHG emissions and natural resource consumption (negative numbers in Fig. 3) but more significant for ecosystems (positive numbers in Fig. 3). The evolution of the impacts during each period shows that, for most regions and economic sectors, the environmental impacts are more important in the bioenergy scenario in 2005–2010 than in the baseline scenario. This tendency, which was already observed in Dandres et al. [28], was attributed to a rebound effect impacting the coal market (increasing coal consumption) and caused by the significant reduction in EU coal consumption due to the rise of bioenergy in Europe. In the current study, the rebound effect and its related environmental impacts are considerably less significant than in Dandres et al. [28], especially because resource consumption and pollutant emissions are reduced when considering technological innovation. Nevertheless, human health, global warming and natural resources are still significantly affected by the 2005–2010 rebound effect. The overall benefits of the bioenergy scenario relative to the baseline scenario are considerably reduced (by 33% on average) by the indirect environmental impacts occurring in 2005–2010 (negative numbers in Table 3). Therefore, if the 2005–2010 coal rebound effect could be avoided, the human health, global warming and natural resources benefits obtained from the bioenergy scenario relative to the baseline scenario could be enhanced by an average of 33%. This information would be useful

Table 3
Contribution of the rebound effect to the total environmental impacts.

Damage category	Contribution
Human health	−45%
Ecosystems	69%
Global warming	−34%
Natural resources	−20%

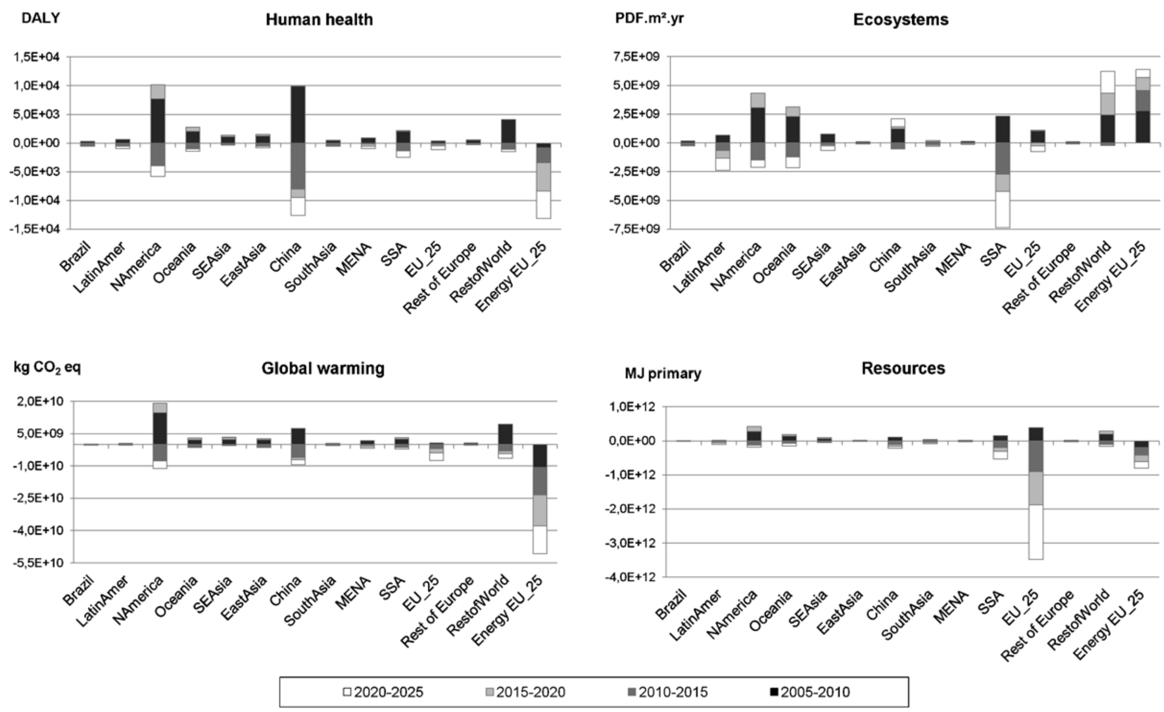

Fig. 4. Comparison of the estimated potential environmental impacts of both scenarios by region based on IMPACT2002+.

when setting out policies, making it possible to reedit a bioenergy policy (with lesser changes in coal consumption) and reassess it using the M-LCA approach in order to curb the coal rebound effect and enhance the benefits of the policy relative to the baseline policy.

3.1.2. By region and economic sector

The comparison of the direct and indirect environmental impacts of the baseline and the bioenergy scenarios at the regional level shows the heterogeneous distribution of environmental impacts between regions (Fig. 4). As illustrated in Fig. 4, the main differences between both scenarios lie in the EU, North America, China, Sub-Saharan Africa and the former USSR. A possible interpretation of the result for the EU is that coal consumption is less significant in the bioenergy scenario than in the baseline scenario. Therefore, human health impacts, greenhouse gases emissions and natural resource consumption are lower than in the baseline scenario. At the same time, the bioenergy policy enhances biomass production, increasing the impacts on ecosystems relative to the baseline scenario. In North America and the former USSR, the indirect environmental impacts are expected to be more significant in the bioenergy scenario owing to the higher economic activity generated by the coal extraction, wood and electricity generation sectors relative to the baseline scenario. In China, the expected increase in wood production in the bioenergy scenario causes more impacts on ecosystems than in the baseline scenario, while decreased coal extraction in the bioenergy scenario generates fewer impacts on human health and global warming than in the baseline scenario. The results also show that coal extraction is considerably less significant in the bioenergy scenario for Sub-Saharan Africa, and the impacts on regional ecosystems are therefore substantially reduced. Also, for the four indicators considered in this study, the indirect environmental impacts are higher in the bioenergy scenario than in the baseline scenario in North America, East Asia, South East Asia, Oceania and the former USSR. However, these four indicators lead to fewer impacts in Brazil, South Asia, the Middle East and North Africa. For the other regions, the comparison of the two scenarios depends on the indicator: the bioenergy scenario presents better results for some indicators and worse results for others.

At the global scale, the bioenergy scenario strongly affects the coal, wood and electricity sectors, resulting in a significant difference in the environmental impacts of the two scenarios (Fig. 5). The environmental impact analyses by economic sector in the three following sections describe the processes that led to the disturbances observed for these three sectors and show several levels of bioenergy policy consequences. The impacts on coal and wood markets highlight the trade relations between the EU and other regions, while electricity sector disturbances are interpreted to be indirect consequences of the increase in industrial activity in certain regions.

3.1.2.1. Economic impacts on the coal market. According to the GTAP7 database, prior to 2005, the EU mostly imported its coal from Sub-Saharan Africa (SSA) and the former USSR (the EU produced only 17% of its coal requirements), satisfying respectively 26% and 18% of EU coal demand (which represents respectively 75% and 45% of SSA and former USSR coal exports). After 2005, reduced coal consumption in the EU due to the application of both energy policies significantly affected the coal markets of SSA and the former USSR. GTAP results show that 2005–2025 coal exports from SSA and the former USSR are lower in the bioenergy scenario than in the baseline scenario (by 20% and 29%, respectively). This may be seen as the main consequence of the bioenergy policy. Due to the more significant reductions in EU coal imports in the bioenergy scenario, the GTAP model anticipates that SSA and the former USSR will export more coal across Asia in the bioenergy scenario. Simulations results show that coal extraction in SSA is less significant in the bioenergy scenario than in the baseline scenario (by 6.4%) and slightly higher in the former USSR (by 1.4%). Two reasons explain why the reductions in coal imports to the EU are expected to have greater impacts on SSA than the former USSR. First, EU coal imports represent a more significant portion of SSA coal exports (75%) than

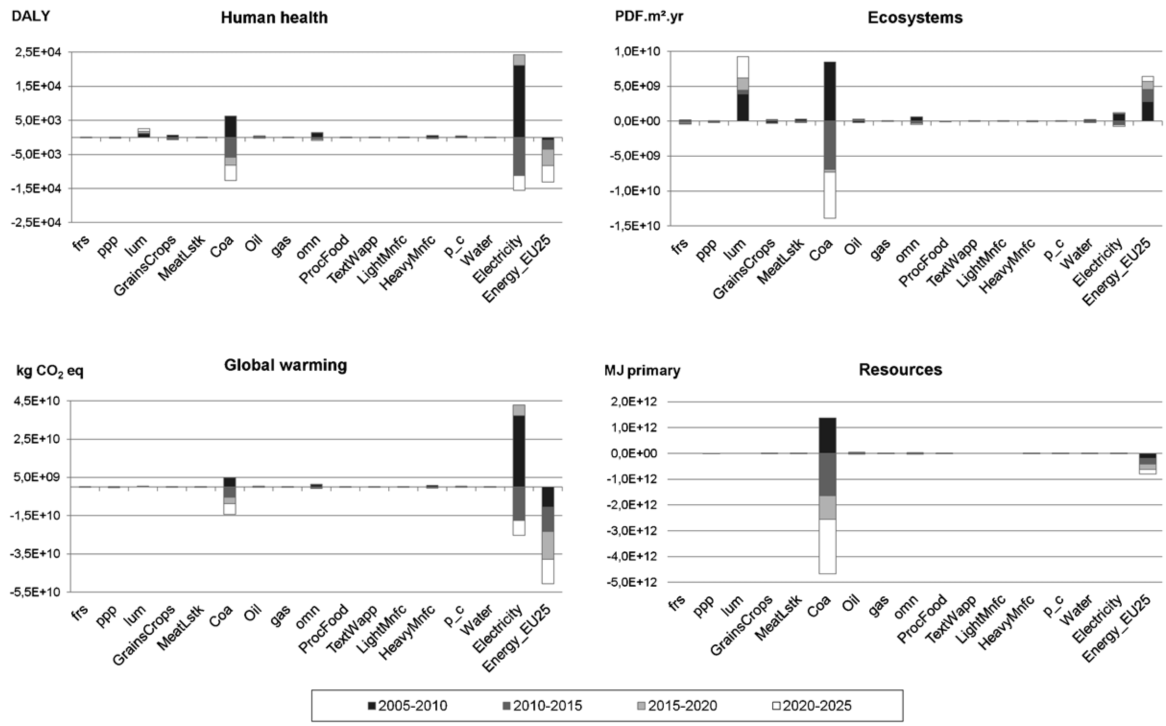

Fig. 5. Comparison of the estimated potential environmental impacts of both scenarios by economic sector based on IMPACT2002+.

exports from the former USSR (45%). Second, the increase in coal exports to Asian regions relative to the baseline scenario is significantly greater from the former USSR than from SSA (by 78%), since coal from the former USSR has penetrated the Asian markets better than coal from SSA.

The increase of coal exports from SSA and the former USSR to Asian regions in the bioenergy scenario relative to the baseline scenario is expected to affect the Asian coal market – a secondary consequence of the bioenergy policy. Based on the results observed in this study, Chinese coal exports to other Asian regions should be the most affected, since, prior to 2005, China was one of Asia's main coal suppliers (Chinese coal exports represent 22% of the coal imported by EAsia, SEAsia and SAsia). Due to the increasing presence of SSA and the former USSR on the Asian market, coal exports from China to other Asian regions are expected to be less important (by an average of 3.8%) in the bioenergy scenario after 2005. In addition, coal extraction in China is expected to be slightly less important in the bioenergy scenario (by 0.3%). A reason that could explain this loss in coal market shares by China is the reduction in coal transport costs from SSA and the former USSR to Asian regions (respectively −1.8% and −1.2%), while the cost from China remains almost unchanged (−0.03%).

3.1.2.2. Economic impacts on the wood market. As expected, wood production is more important in the bioenergy scenario than in the baseline scenario, especially in the EU (by 3.4%) and former USSR (14.1%). The results show an important increase in wood exports from the former USSR, especially to the EU in the bioenergy scenario (+24% compared to baseline scenario). This result is not surprising, since the former USSR is known to have extensive biomass resources [101,102]. In both the baseline and bioenergy scenarios, wood transport prices are expected to decrease in all regions, especially when shipped from the former USSR to other regions (≈20% lower than the average shipping world price). In fact, this may explain why the former USSR increased its wood sales around the world and especially in the EU, significantly intensifying its wood demand in the bioenergy scenario. Also, China reduced its wood imports more than its wood exports in the bioenergy scenario, leading to a slight increase in Chinese wood production (by 0.7%) relative to the baseline scenario. This can be explained by a slightly lower wood transportation price for Chinese exports than for the average world price (by 3.1%).

3.1.2.3. Economic impacts on the electricity market. While it was expected that the wood and coal sectors would be affected by the bioenergy policy, this was not the case for the electricity sector, which posted more significant activity in the bioenergy scenario than in the baseline scenario. Unlike wood and coal, electricity is not traded between all regions of the world (although some local trades may exist between regions). Because the GTAP model is based on trade exchanges, it is difficult to explain the changes occurring in the electricity sector. According to the GTAP results, the main variation in electricity generation between the two scenarios occurs in North America and the former USSR, perhaps due to the fact that the major variations in the production of some of the most electricity-intensive sectors[2] in the two scenarios occur in North America and the former USSR. Indeed, among the sectoral production variation differences observed between the two scenarios, 24% of the difference for the paper and paper pulp sector and 58% of the difference for the mining sector occur in North America, while 52% of the difference for the heavy manufacturing sector occurs in the former USSR. No significant activity variations were observed between the two EU energy scenarios for the other main sectors that consume electricity (transport, communications and services).

3.2. Environmental impacts of EU energy policies and economic growth

Up to this point, the discussion has been conducted by comparing the environmental impacts of the bioenergy scenario relative to those of the baseline scenario in order to focus on the impacts

[2] According to the GTAP7 database.

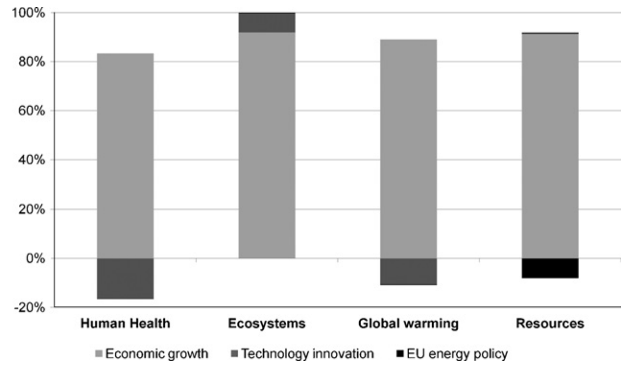

Fig. 6. Contribution of economic growth, technological innovation and EU energy policy to the potential environmental impacts of bioenergy scenario (2005–2025) at the global scale, based on IMPACT2002+.

generated by the implementation of the EU bioenergy policy. In this context, the bioenergy scenario showed a better environmental performance than the baseline scenario for three of the four environmental indicators. Another way to evaluate the EU bioenergy policy is to compare the environmental impacts generated by each policy between 2005 and 2025 without subtracting the impacts of one from the other. This comparison was carried out and led to new observations. When including economic growth in the comparison, natural resource consumption, which is slightly lower in the bioenergy scenario, constitutes the main difference between the scenarios, while the other environmental indicators do not show any significant differences. Additionally, the environmental impacts increase significantly in all impact categories.

Economic growth was expected to contribute to the environmental impacts of each scenario by increasing goods production in every economic sector. Because the economic growth is the same in the two scenarios, the difference between the scenarios can be attributed to the implementation of the EU bioenergy policy, while the common part is related to the economic growth. Therefore, the contribution of the bioenergy policy to the total environmental impacts relative to the baseline policy versus economic growth can be computed. Also, by running the GTAP simulations with and without technological innovation, it is possible to assess its environmental impacts (Fig. 6).

It therefore appears that economic growth is responsible for the significant increase in environmental impacts in 2005–2025, that technological innovation is a secondary factor and that EU energy policy has a negligible effect (except on natural resources). The benefits of the bioenergy scenario are therefore completely offset by economic growth. Even at the European scale, in the bioenergy scenario, GHG emissions increase in 2005–2025 even though the scenario was designed to mitigate GHG emissions. Only the natural resource consumption required by economic growth is slowed by 7.4% in the bioenergy scenario. One of the limitations of the analysis is that carbon taxes and other global warming mitigation measures were not modeled in the current study and could potentially affect the outcome. Therefore, it can only be concluded that the studied bioenergy policy alone will not reduce the environmental impacts in Europe and the rest of the world.

It should also be noted that technological innovation decreases the impacts on human health and global warming but unexpectedly increases the impacts on ecosystems. When modeling technological innovation, the GTAP simulations indicate that the increased impacts on ecosystems are due to the greater demand for water in South Asia. When technological innovation is taken into account, this increase in water demand is related to the significant development of three water-intensive sectors: utilities/construction, transport/communication and other services. For these sectors, the increase in activity is around four times higher when technological innovation is modeled.

3.3. Comparison of M-LCA and C-LCA

In theory, both M-LCA and C-LCA can be used to study the changes occurring in a life cycle. Even though C-LCA was designed to study small changes affecting a small number life cycles, Schmidt et al. [103] used it to study European biofuel policies. Because the biofuel policy studied by Schmidt et al. is different from the one studied in this paper, the two approaches could not be compared. Therefore, the C-LCA approach was applied to the Mantzos scenarios in order to compare the results with the M-LCA approach.

The results of the C-LCA approach show the same trend as the M-LCA approach: the bioenergy scenario leads to fewer impacts on human health, global warming and natural resources but more damages to the ecosystems than the baseline scenario. However, there is a significant difference in indirect environmental impacts between the results of the C-LCA and the M-LCA. While the contribution of the indirect impacts to the total environmental impacts is negligible in the C-LCA approach, they constitute the main part of the total environmental impacts in the M-LCA approach (Table 4). This can be explained by the methodological differences between the two approaches in economy modeling. All the economic sectors and economic growth are modeled in the M-LCA, while only a few economic activities and no economic growth are taken into account in the C-LCA. As previously stated, economic growth is responsible for most of the environmental impacts in the M-LCA approach. Therefore, a substantial variation between the two approaches in terms of the environmental indirect impacts was expected.

The contribution of the indirect environmental impacts to the difference in the total environmental impacts between the two EU energy scenarios is still significant in the M-LCA approach (from 16% to 81% of total impacts), while it remains quasi-negligible (≈1%) in the C-LCA approach (Table 5). The difference is therefore chiefly explained by the number of modeled economic sectors, which differs significantly between the two approaches. With regards to the affected regions, in the two cases set out in the C-LCA approach, the Europe Union is the most affected region and only Eastern Europe and Canada are assumed to be slightly affected by the implementation of the EU bioenergy policy. On the other hand, in the M-LCA approach, the European Union, North America, China, Sub-Saharan Africa and the former USSR are all considerably

Table 4
Contribution of the indirect environmental impacts to the total environmental impacts in the baseline and bioenergy scenarios for the C-LCA and M-LCA approaches.

Environmental impact	Baseline scenario			Bioenergy scenario		
	C-LCA approach		M-LCA approach	C-LCA approach		M-LCA approach
	Low constraints	High constraints		Low constraints	High constraints	
Human health	0.5%	0.5%	99.90	1.5%	1.4%	99.90
Ecosystems	0.0%	0.3%	99.82	0.8%	1.0%	99.82
Global warming	3.4%	3.4%	99.67	1.9%	1.9%	99.67
Natural resources	2.7%	2.7%	92.27	1.5%	1.5%	92.83

Table 5
Contribution of the indirect environmental impacts to the difference in the total environmental impacts between the bioenergy and baseline scenarios for the C-LCA and M-LCA approaches.

Environmental impact	Bioenergy vs. baseline scenario		
	C-LCA approach		M-LCA approach
	Low constraints	High constraints	
Human health	0.3%	6.0%	30.9%
Ecosystems	0.1%	2.6%	40.3%
Global warming	0.1%	1.1%	15.7%
Natural resources	0.0%	1.0%	80.3%

impacted by the EU bioenergy scenario (relative to the baseline scenario).

These differences highlight the need to take the entire economy into account (rather than only a few economic sectors) when studying a large-scale international energy policy. Indeed, using two extreme cases as in the current C-LCA may not be sufficient to adequately portray the indirect environmental impacts potentially caused by significant disturbances, such as the implementation of a continental energy policy. However, the proposed M-LCA approach seems effective in this context since it considers the global economy and all of the changes affecting the EU energy sector (not only biomass supply but also other energy fuel supplies). For instance, using the M-LCA approach, the boundary of the analysis was extended to the indirect effects on the coal market, which proved to be significant to the overall results. Another limitation of the C-LCA approach that did not arise in the M-LCA approach and which also partly explains the differences observed in the results is the fact that consequences are modeled according to the knowledge and data found by the LCA practitioner. In fact, the M-LCA approach models the consequences of a disturbance using a non-linear model programmed according to the commonly accepted neoclassical economic theory. Therefore, the results can be easily reproduced with the M-LCA approach, while some variability may be observed when using the C-LCA approach, especially with regards to the choice of system boundaries and the affected technologies, potentially leading to significant variations in the results [12,104,105].

The C-LCA approach therefore seems better adapted to the analysis of the marginal disturbances impacting a few known economic sectors, while a more advanced approach, like the M-LCA, seems required for large-scale disturbances that could potentially impact the entire economy.

3.4. Sensitivity and uncertainty analysis

The results of the sensitivity and uncertainty analysis are summarized in Table 6, which indicates the probability that the bioenergy scenario results in more environmental impacts than the baseline scenario. The use of different values for the Armington elasticities and the uncertainty of the ecoinvent database and IMPACT2002+ method do not seem to affect the comparison of the EU energy scenarios in terms of sensitivity. The main conclusion remained unchanged: the bioenergy scenario should generate fewer impacts on human health, global warming and natural resource consumption and lead to more ecosystem impacts. The comparison is especially robust for the global warming and resource consumption indicators (probabilities near zero) but remains more uncertain for the human health and ecosystems categories. Indeed, as compared to the baseline scenario, the bioenergy scenario may cause fewer impacts on the ecosystems (average probability of 20.74%) but more on human health (between 19% and 46%). Because no correlation between the uncertainties of these two impact categories was determined, the probability that the bioenergy scenario would cause fewer ecosystem impacts is independent of the probability that this scenario would cause more human health impacts than the baseline scenario. With regards to the Armington elasticities, the trend is that the higher the elasticities (domestic goods are more easily substituted by foreign goods), the higher the probability that the bioenergy scenario will cause more environmental impacts than the baseline scenario. This is especially true for the human health impact category, which is more sensitive to the Armington elasticities.

The uncertainty analysis is limited by the fact that it does not take the uncertainty of the GTAP model, of the data collected from public databases (FAO, UNDATA and IEA databases) or of the mapping between (i) the GTAP7 and ecoinvent databases and (ii) the PRIMES and GTAP models into account. Also, the uncertainty of exogenous variables such as the evolution of economic growth and technological innovation is not taken into account. Finally, the application of other international policies such as a post-Kyoto carbon policy or other continental renewable energy policies outside the EU applied concurrently with the EU energy policy is not considered. Nevertheless, the sensitivity and uncertainty analysis presented here shows that the comparison of the baseline and bioenergy scenarios is not widely affected. Thus, the M-LCA approach can be considered quite robust with regards to the sources of uncertainty that are modeled. However, the sources of uncertainty stated earlier should also be considered in order to assess the global robustness of the M-LCA method. This issue will be addressed in a subsequent study.

4. Conclusion

In this paper, M-LCA, an enhanced LCA methodology that combines both consequential and prospective LCA, was presented and illustrated within the context of a comparison of two European energy policies by integrating economic and temporal aspects. The economic aspects were implemented using the GTAP general equilibrium model, which simulates the economic consequences on regional economic sectors caused by the planned changes of each European energy policy. Then, the environmental impacts brought about by production variations in each economic sector were modeled for each region of the world and each EU energy policy using LCA. The GTAP recursive simulations made it possible to consider the evolution of the forecasted macroeconomy in terms of GDP, capital investment, population growth, labor force and technological innovation as well as the changes brought about by the studied policy. It was possible to distinguish between the direct environmental impacts due to the energy production profile changes outlined

Table 6
Probabilities that the bioenergy scenario would cause more impacts than the baseline scenario.

Environmental impact category	Armington elasticities			Average probability
	Default values −50%	Default values	Default values +50%	
Human health	19.59%	28.01%	45.99%	31.20%
Ecosystems	70.82%	82.62%	84.33%	79.26%
Global warming	0.00%	0.00%	0.00%	0.00%
Natural resources	0.01%	0.10%	1.72%	0.61%

in the studied EU energy policy and the indirect environmental impacts corresponding to the fluctuations in the global economy caused by the application of the policy.

The evaluation of the European energy policies showed that both the direct and indirect environmental impacts substantially contribute to the global environmental impact, and that these indirect impacts may vary significantly between periods, economic sectors and regions. At the global scale and in the long-term, the bioenergy policy based on the increased use of wood biomass to replace coal in EU energy generation was shown to lead to fewer environmental impacts for the human health, global warming and natural resource consumption indicators and greater ecosystem impacts than the baseline policy (a business as usual policy). It was also observed that the difference between the environmental impacts of the two scenarios was not significant in the context of the environmental deterioration that is expected to be caused by economic growth during the energy policy implementation period. Indeed, the benefits of the bioenergy policy relative to the baseline policy would be offset by the environmental impacts generated by economic growth. More specifically, in the bioenergy scenario, EU greenhouses gas emissions would increase as compared to 2005 despite the substitution of coal with biomass. Because carbon taxes and other environmental measures were not modeled, it can only be concluded that the studied bioenergy policy alone will not reduce the environmental impacts at the EU or global scale. The partial sensitivity and uncertainty analysis showed that the comparison of the EU energy policy conducted with the M-LCA approach is quite robust. However, more uncertainty sources should be taken into account in order to assess the global robustness of the M-LCA method. Additionally, the application of several environmental policies, such as a worldwide carbon tax or renewable energy policies in other regions should be considered in order to evaluate their interactions with studied EU energy policies.

The M-LCA approach presented in this paper appears to be a promising development of the LCA methodology, making it possible to model more economic and environmental consequences than C-LCA, when non-marginal variations occur in one or several life cycles. M-LCA also differs from C-LCA in its capacity to include a dynamic background (evolution of populations and technologies). Because of its capacity to model impacts according to several impact categories based on life cycle methodology, the approach also constitutes a useful tool for GTAP users seeking to investigate the environmental impacts brought about by economic changes.

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Appendix A.

Table A1
Definition of GTAP regions.

GTAP region (description)	Member countries
Oceania	Australia, New-Zealand, American Samoa, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Marshall, Micronesia, Nauru, New Caledonia, Norfolk Island, Northern Mariana Islands, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis and Futuna
China	China
EastAsia	Hong-Kong, Japan, Korea (north and south), Taiwan, Macau, Mongolia
SEAsia (South East Asia)	Cambodia, Indonesia, Lao, Myanmar, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Brunei Darussalam, Timor Leste
SAsia (South Asia)	India, Pakistan, Bangladesh, Sri Lanka, Afghanistan, Bhutan, Maldives, Nepal
NorthAmer (North America)	Greenland, Canada, United States, Mexico, Bermuda, Saint Pierre and Miquelon
LatinAmer (Latin America)	Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Falkland Islands, French Guiana, Guyana, Suriname, Belize, Costa Rica, Guatemala, Nicaragua, Panama, El Salvador, Honduras, Antigua and Barbuda, Bahamas, Barbados, Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and Grenadines, Trinidad and Tobago, Virgin Islands (US and British), Anguilla, Aruba, Cayman Islands, Cuba, Guadeloupe, Martinique, Montserrat, Netherlands Antilles, Turks and Caicos
Brazil	Brazil
EU_25 (European Union)	Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom
RestofEU (Rest of Europe)	Norway, Switzerland, Albania, Bulgaria, Croatia, Romania, Iceland, Liechtenstein, Andorra, Bosnia and Herzegovina, Faroe Island, Gibraltar, Macedonia, Monaco, San Marino, Serbia and Montenegro, Moldova
MENA (Middle East and North Africa)	Iran, Turkey, Egypt, Morocco, Tunisia, Algeria, Libya, Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Palestinian occupied territory, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen
SSA (Sub-Saharan Africa)	Nigeria, Senegal, Ethiopia, Madagascar, Malawi, Mauritius, Mozambique, Tanzania, Uganda, Zambia, Zimbabwe, Botswana, South Africa, Benin, Burkina Faso, Cote d'Ivoire, Cape Verde, Ghana, Guinea, Guinea-Bissau, Gambia, Liberia, Mali, Mauritania, Niger, Saint Helena, Sierra Leone, Togo, Central African Republic, Cameroon, Congo, Gabon, Equatorial Guinea, Sao Tome and Principe, Chad, Angola, Congo, Burundi, Comoros, Djibouti, Eritrea, Kenya, Mayotte, Reunion, Rwanda, Somalia, Sudan, Seychelles, Lesotho, Namibia, Swaziland
RestofWorld (Former USSR)	Russian Federation, Ukraine, Kazakhstan, Kyrgyzstan, Armenia, Azerbaijan, Belarus, Georgia, Tajikistan, Turkmenistan, Uzbekistan

Table A2
Definition of GTAP economic sectors.

GTAP sector	Description	Detail
GrainsCrops	Grains and crops	Paddy rice, wheat, cereal grains, vegetables, fruit, nuts, oil seeds, sugar cane, sugar beet, plant-based fibers, crops, processed rice
MeatLstk	Livestock and meat products	Cattle, sheep, goats, horses, other animal products, raw milk, wool, silk-worm cocoons, fishing
ProcFood	Processed food	Vegetable oils and fats, dairy products, sugar, food products, beverages and tobacco products
Water	Water	Collection, purification and distribution of water
TextWapp	Textiles and clothing	Textiles, wearing apparel
LightMnfc	Light manufacturing	Leather products, metal products, motor vehicles and parts, transport equipment, manufactures.
HeavyMnfc	Heavy manufacturing	Chemical, rubber, plastic prods, mineral products, ferrous metals, metals, electronic equipment, machinery and equipment
Util_Cons	Utilities and construction	Construction
TransComm	Transport and communication	Land transport, transport via pipelines, water transport, air transport, post and telecommunications
OthServices	Other services	Financial services, insurance, business services, recreation and other services, public administration, defense, health, education, dwellings.
Coa	Coal and lignite extraction	Mining and agglomeration of hard coal and lignite
Gas	Gas extraction	Extraction of natural gas, service activities incidental to natural gas extraction excluding surveying
Oil	Oil and peat extraction	Extraction of crude petroleum, service activities incidental to oil extraction excluding surveying
Omn	Minerals	Mining and quarrying (including uranium)
p_c	Fuels	Manufacture of coke oven products and refined petroleum products, processing of nuclear fuel
Gdt	Gas, steam and hot water	Manufacture of gas, distribution of gaseous fuels through mains, steam and hot water supply
Ely	Electricity	Production, collection and distribution of electricity
Frs	Forestry	Forestry, logging and related service activities
Ppp	Pulp, paper, publishing	Manufacture of paper and paper products, publishing, printing and service activities related to printing
Lum	Wood products	Manufacture of wood and of products of wood and cork, except furniture, Manufacture of articles of straw and plaiting materials

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